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Energy for generations

STOVE PERFORMANCE TEST REPORT FOR EOCEYE Stove (SSM S32-13)

Cookstove Samples: 2019/B053, 2019/B054, 2019/B055, 2019/B056, 2019/B057, 2019/B058

Test Report No: B/TR/2019/027

CENTRE FOR RESEARCH IN ENERGY AND ENERGY CONSERVATION
24 Oct 2019
CEDAT
MAKERERE UNIVERSITY

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OCTOBER 2019

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Acronyms and abbreviations

Acronym	Term or definition
CI	confidence interval
CO	carbon monoxide
CO2	carbon dioxide
g	gram
kg	kilogram
kW	kilowatt
m	meter
mg	milligram
min	minute
MJ	megajoule
MJd	megajoule useful energy delivered
PM2.5	particulate matter with an aerodynamic diameter ≤ 2.5 microns
SD	standard deviation
CEDAT	College of Engineering Design Art and Technology
COV	Coefficient of Variation
CREEC	Centre for Research in Energy and Energy Conservation
ISO	International Standards Organisation
RTKC	Regional Testing and Knowledge Centre
WBT	Water Boiling Test

1. Description of cookstove system tested

A cookstove system consists of the stove, cooking vessel, fuel, and operating procedure. The operating procedure used for testing the cookstove was as per client instructions. The cookstove was delivered to the testing laboratory by the client.

Type of cookstove

The cookstove referred to as EOCEYE stove (SSM S32-13) is a natural draft wood fuel stove designed for household cooking. Two sample were delivered, received and registered at the regional test and knowledge centre (RTKC), CREEC. The delivery comprised identical samples, three previously used stoves and three newly built stoves.

Construction materials

The cookstove has an overall structure made of sheet metal, metal casting at the top stove covering and stainless-steel handles covered with plastic

Stove description

The stove is composed of a fully insulated vertical combustion chamber that forces gases to mix with flames when in use, the combustion chamber is lined with a refractory metal sheet. The rigid stainless-steel handles are covered with silicone grips to ensure they stay cool even when the stove is hot.

Fig 1. Used Samples

Fig 2. New samples

The stoves were assigned laboratory codes for easy identification. Three used stove samples delivered had serial numbers and were assigned lab codes ***295181001226***(2019/B056), ***295181006151***(2019/B054) and ***295181001866***(2019/B057) while the new samples were only assigned laboratory codes 2019/B053, 2019/B055 and 2019/B058 for easy laboratory identification. The stoves typically use firewood as a fuel, and they are cylindrical in shape.

Table 1. Stove description for Used and New samples

Parameters	Unit	EOCEYE Stove (SSM S32-13) Used Samples				EOCEYE Stove (SSM S32-13) New Samples				New & used sample combined		
Stove serial number		**295181006151**	**295181001866**	**295181001226**								
Stove sample code		**2019/B054**	**2019/B056**	**2019/B057**	**Average**	**2019/B053**	**2019/B055**	**2019/B058**	**Average**	**Average**	**STDeV**	**CoV**
Stove weight	g	9266	9088	8717	9024	8196	8499	8456	8384	8703.67	406.22	5%
Top diameter of the stove	cm	32	32	32	32	32	32	32	32	32	0	0%
Bottom diameter of the stove	cm	23	23	23	23	23	23	23	23	23	0	0%
Stove top thickness	cm	1	1	1	1	1	1	1	1	1	0	0%
Combustion chamber diameter	cm	9	9	9	9	9	9	9	9	9	0	0%
Combustion chamber height	cm	16	16	16	16	15.5	15.5	15.5	15.5	15.75	0.27	2%
Length of primary air inlet	cm	11.7	11.7	11.7	11.7	12.0	12.0	12.0	12	11.9	0.16	1%
Height of primary air inlet	cm	9	9	9	9	9	9	9	9	9	0	0%
Area of primary air inlet	sq.cm	105	105	105	105.3	108.0	108.0	108.0	108	107	1.48	1%
Number of primary air holes		1	1	1	1	1	1	1	1	1	0	0%
Pot rest height	cm	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	0	0%
Pot rest length	cm	5	5	5	5	5.5	5.5	5.5	5.5	5.3	0.27	5%
Distance of handles from stove body	cm	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	0	0%
Stove height above ground	cm	31.4	31.4	31.4	31.4	32	31.5	31.3	31.6	31.5	0.25	1%
Length/diameter of the grate	cm	3.5	3.5	3.5	3.5	3.4	3.4	3.4	3.4	3.5	0.05	2%
Number of holes on the grate		12	12	12	12	12	12	12	12	12	0	0%
Length of wood rest	cm	22.5	22.5	22.5	22.5	22.6	22.6	22.6	22.6	22.6	0.05	0%
Skirt height	cm	7	7	7	7	7	7	7	7	7	0	0%
Skirt thickness	cm	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0	0%
Skirt diameter	cm	29.5	29.5	29.5	29.5	30	30	30	30	29.75	0.27	1%

Cooking vessel

A flat-bottomed aluminium pot of 7 litres capacity was used to boil 5 litres of water. The pots had diameter ranges of 26.5 cm and a height of 13.0cm. The pots were cylindrical in shape.

Component/dimension measurement

Fig 3. 7 litre flat Aluminium pot

Fuel description/biomass species

Air dried *Eucalyptus grandis* wood with average dimensions of ***3 cm x 3 cm x 30*** cm was used. The wood fuel had a measured high heating value (dry matter) of 18,253.45KJ/kg with moisture content of ranging between 12%-15%. The fuel was sourced from a single supplier

Fig 4. Fuel wood used during the tests

Operational conditions

The operating conditions at the laboratory were as follows:

- Ambient temperature (°C): 21.4^0C – 25.0 deg C
- Altitude (m): 1240m above sea level
- Local boiling point (°C): 95.5 $\pm$1 deg C

Tests done

Tests conducted on the samples include investigation of thermal performance and emission monitoring that include gaseous emissions (Carbonmonoxide CO, carbondioxide CO_2 and aerosol emissions (particulate matter, $PM_{2.5}$) at three test phase simulating normal regular household cooking practices.

2. Test protocols

Water Boiling Test

The Water Boiling Test (WBT) is a simplified simulation of the cooking process. It is intended to measure how efficiently a stove uses fuel to heat water in a cooking pot. The Water Boiling Test was developed to assess stove performance in a controlled manner, and thus it is probably less like local cooking. The test reveals the technical performance of a stove, not necessarily what it can achieve in real households. Some of the parameters measured during a WBT include thermal efficiency, specific fuel consumption, time to boil, burning rate, turn-down ratio and fire power.

The cookstoves were tested using the Water Boiling Test (WBT) protocol version 4.2.3 (GACC, 2014)[1]. Three test replicates were done for each stove sample. All three WBT phases were conducted i.e.:

- High-power (cold-start): Five litres of water were brought to a boil in a 7-litre pot using a stove at ambient temperature
- High-power (hot-start): Five litres of water were brought to a boil in a 7-litre pot using a pre-heated stove.
- Low-power (simmering): The water temperature is kept at about 3° C below boiling point for 45 minutes.

For each test phase, the measured parameters included time taken, mass of fuel used, mass of water in pot and the mass of charcoal created.

3. Measurement methods

The laboratory is equipped with the LEMS (Laboratory Emissions Measurement System that measures gaseous emissions (i.e., carbon monoxide and carbon dioxide) and the gravimetric system which provides a direct measurement of the total $PM_{2.5}$.

Fig 5. LEMS setup

Fig 6. PM Sampling train and Calibration gases

Fig 7. PM2.5 Filter holder

Fig 8. Microbalance scale for filters

Fig 9. Balance scale for water and fuel measurement

In the $PM_{2.5}$ system, the exhaust is sampled from the duct and goes through an ultra-sharp cut $PM_{2.5}$ cyclone to remove particles larger than 2.5µm). The flow through the cyclone is controlled by a precision, 16.7 LPM, critical orifice. Particles less than 2.5µm are deposited on a fiber glass filter that is humidity conditioned and weighed on a calibrated microbalance both before and after each experiment. The difference in mass of the filter before and after testing yields the emission of $PM_{2.5}$. It should be noted that the "Gravimetric $PM_{2.5}$ system" and the "Real-time aerosol system" do not share the same exhaust sampling line but are sampled from the same location in the duct.

The facility also contains the Testo moisture meter for measuring moisture content of the fuel wood; a thermocouple logger for measuring water ambient temperature, 30kg scale for water and fuel measurement, desiccator and desiccator chamber.

4. Performance test results

Table 2. Showing performance of Ecoeye new samples

****Test results based on 3 tests for the new samples tested with pot skirt*

		Metrics	Value	Units	Sub-Tier
Efficiency/Fuel Use					
Tier	**2**	High power Thermal Efficiency	**38.6**	%	**3**
		Low power Specific Consumption	**0.031**	MJ/min/l	**2**
Emissions					
Tier	**1**	High power CO	**8.90**	g/MJd	**3**
		Low power CO	**0.16**	g/min/l	**1**
		High power PM 2.5	**576.52**	mg/MJd	**1**
		Low power PM 2.5	**5.93**	mg/min/l	**1**
Indoor emissions					
Tier	**0**	Indoor emissions CO	**0.66**	g/min	**1**
		Indoor emissions PM 2.5	**40.36**	Mg/min	**0**

Tier 0 → Improving Performance →Tier 4

Table 3. Showing performance Ecoeye used samples

****Test results based on 3 tests for the Used stove samples with pot skirt*

		Metrics	Value	Units	Sub-Tier
Efficiency/Fuel Use					
Tier	**2**	High power Thermal Efficiency	**40.5**	%	**3**
		Low power Specific Consumption	**0.033**	MJ/min/l	**2**
Emissions					
Tier	**1**	High power CO	**9.40**	g/MJd	**2**
		Low power CO	**0.15**	g/min/l	**1**
		High power PM 2.5	**536.05**	mg/MJd	**1**
		Low power PM 2.5	**6.13**	mg/min/l	**1**
Indoor emissions					
Tier	**1**	Indoor emissions CO	**0.70**	g/min	**1**
		Indoor emissions PM 2.5	**37.75**	Mg/min	**1**

Tier 0 → Improving Performance →Tier 4

5. Discussion of results

Tests results highlight thermal performance at high power performance, formally used stoves scored higher than the unused stoves despite the identical physical properties. Using a pot skirt drastically increases stove thermal efficiency. This increase is ascribed by increased useful heat transfer to the pot's peripheral wall and minimal heat loss to the environment as waste heat in the plume. The graphs below show the emissions trends for the two samples.

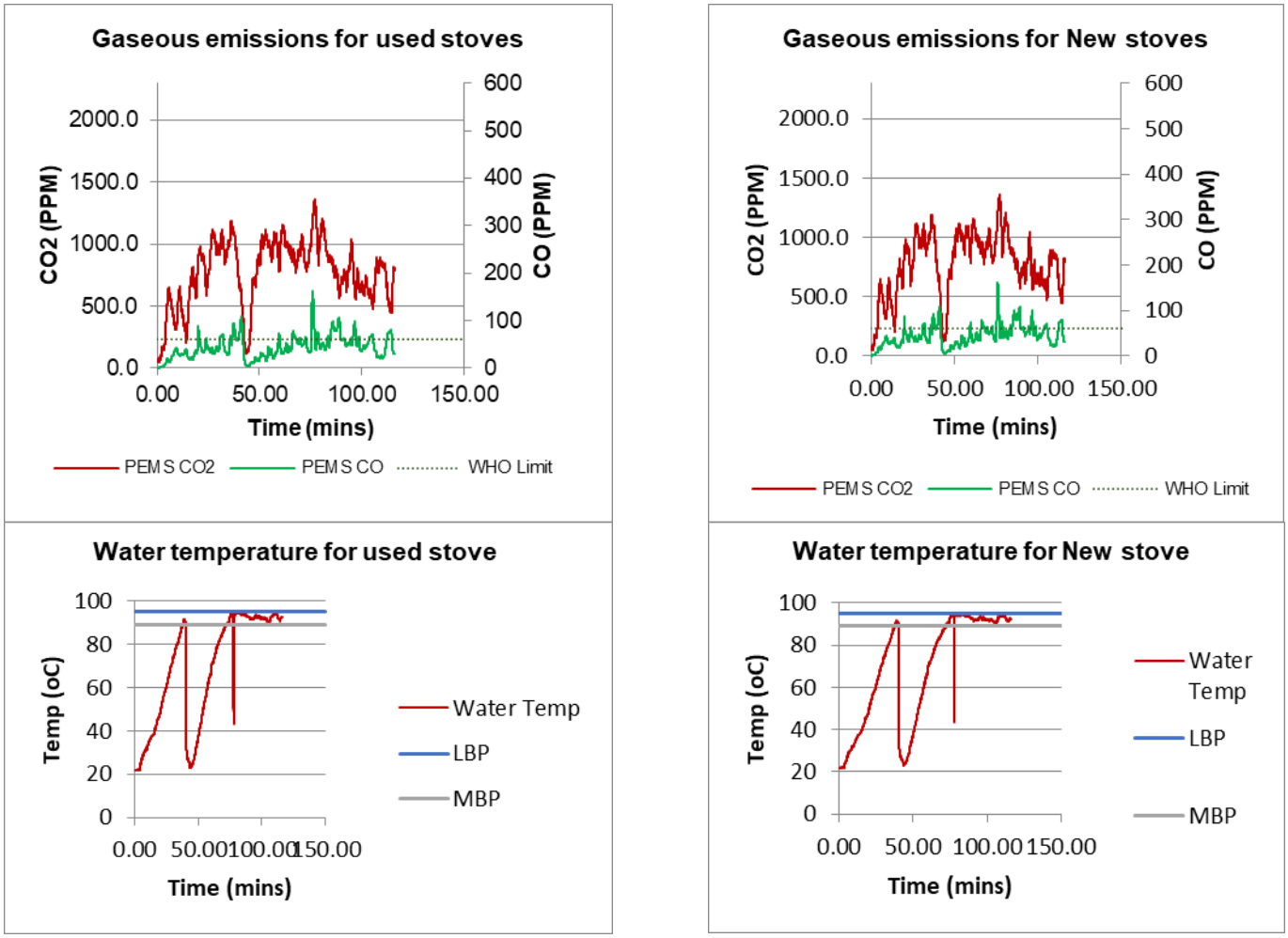

Fig 10. Graphs for gaseous emissions and temperature for the stove samples

Thermal and mechanical properties of the refractory insulation is not known to the tester; however, it is highly suspected that the mainly reason for the difference in the thermal performance lies in the properties of the insulating materials. This evaluation was made in regard to thermal stress, thermal conductivity and porosity of the refractory insulating medium.

As a way to validate this suspicion, an investigate step was conducted on both stove regimes. A non-destructive evaluation approaches such as observation was employed, the state of insulation was evaluated, and the following findings were derived;

a) Resistance to thermal stress decreases with increasing porosity.
b) Increasing porosity lowers thermal conductivity.
c) Strength is reduced and porosity increased substantially by tensile thermal stress.

The above three reasons underpin the variation in thermal performance of the two stove regimes. Previously used stoves are assumed to have been exposed to tensile thermal stress as such, gaining a high level of porosity and thus decrease in thermal conductivity around the combustion chamber. In this instance, useful energy is maximized accounting for the increase in thermal performance of previously used stoves. Statistical analysis was done to evaluate the differences in the two stove regimes.

High Power Thermal Efficiency (%)

Units	USED EOCEYE	NEW EOCEYE
Test 1	39.1%	37.3%
Test 2	43.6%	39.0%
Test 3	40.4%	37.2%
Test 1	37.5%	39.0%
Test 2	40.4%	39.1%
Test 3	39.7%	36.2%
Test 1	40.0%	39.0%
Test 2	39.4%	39.5%
Test 3	44.6%	41.1%
Average	40.5%	38.6%

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
USED	9	3.6473	0.405254	0.0004914
NEW	9	3.4738	0.385973	0.0002171

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*
Between Groups	0.00167286	1	0.00167	4.722338096	0.04514
Within Groups	0.00566791	16	0.00035		
Total	0.00734077	17			

F>Fcrit (4.722338>4.493998), therefore there is a significant statistical difference between the high-power thermal efficiency of USED EOCEYE and NEW EOCEYE.

Low Power Specific Consumption Rate (MJ/min/L)

Units	USED EOCEYE	NEW EOCEYE
Test 1	0.038	0.031
Test 2	0.036	0.029
Test 3	0.030	0.033
Test 1	0.036	0.032
Test 2	0.029	0.032
Test 3	0.028	0.025
Test 1	0.040	0.032
Test 2	0.031	0.031
Test 3	0.028	0.030
Average	0.033	0.031

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
USED	9	0.2956	0.032848	2.04E-05
NEW	9	0.2754	0.030597	5.844E-06

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2.2795E-05	1	2.3E-05	1.736987372	0.20608	4.494
Within Groups	0.00020997	16	1.3E-05			
Total	0.00023276	17				

F<Fcrit (1.736987372<4.493998), therefore there is **NO** significant statistical difference between the Low Power Specific Consumption Rate of USED EOCEYE and NEW EOCEYE.

6. Quality Assurance/Quality Control

Quality control is of utmost concern to the CREEC cookstove testing laboratory. A series of protocols and methods ensures that all tests undertaken at the cookstove facility are performed by well-trained personnel using calibrated equipment and rigorous standardized testing procedures.

Scale calibration

The mass on the filter is measured separately using an electronic balance CX 265 model carrying a maximum capacity of 220g and calibrated annually by Uganda National Bureau of Standards. For quality checklist, reference weights of 50g, 100g±0.15mg are weighed before the start of the test to ensure no variations in the measurement. 1kg mass and 10 kg reference weights are also weighed onto the 30kg scale balance to ensure consistence of measurement.

The mass on the filter is related to the mass emitted from the stove using the volumetric flow rate at the sample location. Upon starting the pump at the beginning of every test, the vacuum gauge should show a vacuum greater than 16" Hg. Between every test it should always be within 1" Hg of the average. If the value is much higher than the average, the critical orifice is checked if it has clogged. A leak check on the gravimetric system, CO Concentration and CO_2 Concentration is done before each test. The LEMS gas analyzer is also calibrated for span using 300 ppm CO and 3000 ppm CO2 calibration gases.

Protocol to ensure quality control in testing procedures

All personnel in the CREEC cookstove facility undertake rigorous training in the testing procedure before embarking on testing the stove. At least two trained personnel are present for every test. At the beginning of the test, a checklist is done on the setup to ensure accuracy. Prior to each test, stoves and pots are scrubbed clean with a dry brush. This step prevents the accumulation of soot and tar that could impact heat transfer in successive replicate tests. For a wood burning stove, a fire is typically started using kerosene/ ethanol and kindling or starters.

Fuel wood (specified dimension) is then added to the fire progressively to heat the water from ambient temperature to boiling. Both the kindling and the fuel-wood are untreated and harvested from a single source and stored in a dry location prior to the experiments. This fire startup procedure is followed unless specific instructions are provided for testing a stove.

7. Conclusion

Exposure of refractory material to thermal stress improves its porosity and hence lowering thermal conductivity. Therefore, its theoretically feasible for a previously used stove to score a higher thermal efficiency than an identical newly built stove with the same properties. This claim is there in reflected in the experimental results.

8. APPENDICES

Appendix 1: Detailed performance results for new EOCEYE stove

Stove type/model		2019/B053			2019/B055			2019/B058					
IWA Performance Metrics	**Units**	**Test 1**	**Test 2**	**Test 3**	**Test 1**	**Test 2**	**Test 3**	**Test 1**	**Test 2**	**Test 3**	**Average**	**STDeV**	**CoV**
High Power Thermal Efficiency	%	37.3%	39.0%	37.2%	39.0%	39.1%	36.2%	39.0%	39.5%	41.1%	38.6%	0.01	4%
Low Power Specific Consumption Rate	MJ/min/L	0.031	0.029	0.033	0.032	0.032	0.025	0.032	0.031	0.030	0.031	0.00	8%
High Power CO	g/MJd	10.11	8.12	11.26	7.71	7.16	9.20	9.66	8.20	8.72	8.90	1.29	14%
Low Power CO	g/min/L	0.19	0.13	0.17	0.16	0.17	0.17	0.16	0.14	0.14	0.16	0.02	11%
High Power PM	mg/MJd	679.6	623.2	557.2	458.4	522.3	524.4	629.3	521.6	672.5	576.52	77.30	13%
Low Power PM	mg/min/L	7.79	4.01	6.68	6.42	5.57	5.46	6.38	5.56	5.48	5.93	1.05	18%
Indoor Emissions CO	g/min	0.72	0.57	0.80	0.60	0.64	0.66	0.67	0.59	0.68	0.66	0.07	11%
Indoor Emissions PM	mg/min	46.5	44.0	39.3	26.1	35.5	38.0	43.9	38.3	51.7	40.36	7.34	18%
IWA Performance Tier		**Tier**	**Tier**	**Tier**	**Tier**	**Tier**	**Tier**	**Tier**	**Tier**	**Tier**	**Sub Tier**	**Tier**	
High Power Thermal Efficiency		3.2	3.4	3.2	3.3	3.4	3.1	3.3	3.4	3.6	3	2	
Low Power Specific Consumption Rate		2.7	2.8	2.5	2.6	2.6	3.2	2.6	2.7	2.8	2		
High Power CO		2.4	3.8	1.9	4.0	4.1	2.8	2.6	3.7	3.2	3	1	
Low Power CO		1.1	1.9	1.4	1.5	1.4	1.4	1.6	1.8	1.8	1		
High Power PM		1.5	1.5	1.7	1.8	1.7	1.7	1.5	1.7	1.5	1		
Low Power PM		1.0	1.9	1.3	1.3	1.6	1.6	1.4	1.6	1.6	1		
Indoor Emissions CO		1.7	2.4	1.4	2.1	1.9	1.8	1.8	2.2	1.8	1	0	
Indoor Emissions PM		0.8	0.9	1.0	1.6	1.1	1.0	0.9	1.0	0.7	0		
Safety		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0			
Standard Performance Measures													
Fuel to Cook 5L (850/1500)	g	754.9	732.5	802.6	772.7	772.4	707.0	761.6	759.1	721.1	753.76	29.34	4%
CO to Cook 5L (20)	g	63.5	47.7	62.5	52.9	54.3	59.1	56.3	51.0	51.4	55.41	5.40	10%
PM to Cook 5L (1500)	mg	3177.9	2267.1	2756.6	2458.1	2455.5	2449.2	2801.4	2457.5	2702.7	2614.00	274.47	11%
Energy to Cook 5L (15,000/25,000)	kJ	12,783	12,403	13,591	13,084	13,079	11,972	12,896	12,854	12,211	12763.69	496.83	4%
Time to Boil	min	29.4	30.2	30.9	37.6	31.8	31.7	29.7	30.8	27.2	31.04	2.82	9%
CO2 to Cook 5L	g	1093.3	1183.7	1226.7	1391.5	1306.9	1238.4	1327.5	1241.6	1114.6	1236.01	97.18	8%
Basic Operation													
COLD START													
Time to boil Pot # 1	min	30	32	37	39	33	37	33	36	27	33.76	3.81	11%
Burning rate	g/min	10.56	10.56	10.13	7.66	9.76	8.84	10.14	9.65	10.68	9.78	0.98	10%
Thermal efficiency	--	36%	36%	35%	38%	38%	37%	36%	38%	41%	**37.3%**	0.02	5%
Specific fuel consumption	g/liter	66.73	70.29	79.26	63.76	67.98	69.93	70.96	74.21	61.69	69.42	5.29	8%
Temp-corrected specific consumption	g/liter	68.0	72.3	80.9	65.0	68.2	69.6	72.2	75.2	62.5	70.43	5.51	8%
Firepower	watts	2,981	2,979	2,860	2,163	2,754	2,494	2,861	2,722	3,014	2758.81	276.26	10%
Equivalent Dry Fuel Consumed	g	316.7	333.8	370.4	302.7	320.1	329.3	334.5	343.7	293.5	327.20	22.73	7%
HOT START													
Time to boil Pot # 1	min	28	27	24	34	31	26	25	25	26	27.42	3.13	11%
Burning rate	g/min	11.33	11.02	12.63	9.65	10.75	14.19	11.43	12.00	11.67	11.63	1.27	11%
Thermal efficiency	--	38%	42%	39%	40%	40%	35%	42%	41%	41%	**39.9%**	0.02	5%

Specific fuel consumption	g/liter	66.88	63.07	63.58	70.63	71.04	81.08	61.47	64.60	64.84	67.47	6.06	9%
Temp-corrected specific consumption	g/liter	68.2	64.9	64.9	72.4	71.2	80.8	62.6	65.5	65.7	68.45	5.60	8%
Firepower	watts	3,197	3,110	3,564	2,725	3,035	4,004	3,224	3,387	3,293	3281.95	357.68	11%
Equivalent Dry Fuel Consumed	g	315.1	297.7	303.3	328.7	330.1	375.5	289.2	302.6	305.3	316.39	25.99	8%
SIMMER													
Burning rate	g/min	7.11	6.45	7.22	7.18	7.15	5.44	7.13	6.85	6.60	6.79	0.58	8%
Thermal efficiency	--	37%	46%	44%	38%	36%	53%	41%	41%	46%	**42.4%**	0.05	13%
Specific fuel consumption 45 min	g/liter	82.9	77.9	87.6	85.9	84.8	66.2	84.9	81.5	80.1	81.31	6.42	8%
Firepower	watts	2,007	1,822	2,038	2,025	2,017	1,535	2,012	1,933	1,862	1916.79	162.72	8%
Turn down ratio	--	1.54	1.67	1.58	1.21	1.43	2.12	1.51	1.58	1.69	1.59	0.24	15%
Equivalent Dry Fuel Consumed	g	320.1	290.4	324.9	322.9	321.7	244.7	320.7	308.2	297.0	305.63	25.95	8%
Energy Consumption													
Net Calorific Value (dry)	kJ/kg	16,933	16,933	16,933	16,933	16,933	16,933	16,933	16,933	16,933	16933.45	0.00	0%
Moisture Content	%	14%	14%	14%	14%	14%	14%	14%	14%	14%	14%	0.00	0%
COLD START													
Temp-Corrected Time to Boil	min	30.6	32.5	37.3	40.3	32.9	37.1	33.6	36.1	27.9	34.24	3.82	11%
Energy Consumption Rate	kJ/min	179	179	172	130	165	150	172	163	181	165.53	16.58	10%
Temp-Corr Specific Energy Consumption	kJ/liter	1,151	1,224	1,370	1,100	1,154	1,179	1,223	1,274	1,059	1192.70	93.28	8%
Specific Energy Consumption Rate	MJ/min/L	0	0	0	0	0	0	0	0	0	0.04	0.00	10%
Dry Fuel Consumed		330	346	385	314	333	339	347	357	305	339.70	23.54	7%
Total Energy Consumed	kJ	5,586	5,866	6,518	5,324	5,645	5,742	5,881	6,045	5,164	5752.33	398.64	7%
Energy Delivered to the Cooking Pot	MJ	1.944	2.044	2.210	1.958	2.060	2.068	2.037	2.217	2.029	2.06	0.10	5%
Average Cooking Power	kW	1.061	1.047	0.988	0.811	1.044	0.929	1.011	1.023	1.214	1.01	0.11	11%
HOT START													
Temp-Corrected Time to Boil	min	28.3	27.8	24.5	34.9	30.8	26.4	25.8	25.6	26.5	27.84	3.22	12%
Energy Consumption Rate	kJ/min	192	187	214	163	182	240	193	203	198	196.92	21.46	11%
Temp-Corr Specific Energy Consumption	kJ/liter	1,154	1,099	1,099	1,225	1,206	1,367	1,059	1,109	1,113	1159.03	94.88	8%
Specific Energy Consumption Rate	MJ/min/L	0	0	0	0	0	0	0	0	0	0.04	0.00	11%
Dry Fuel Consumed		328	309	316	341	344	386	301	315	317	328.62	25.83	8%
Total Energy Consumed	kJ	5,557	5,240	5,353	5,775	5,819	6,543	5,095	5,331	5,368	5564.63	437.34	8%
Energy Delivered to the Cooking Pot	MJ	2.044	2.109	2.007	2.213	2.249	2.249	2.057	2.097	2.142	2.13	0.09	4%
Average Cooking Power	kW	1.202	1.265	1.365	1.057	1.218	1.422	1.331	1.368	1.346	1.29	0.11	9%
SIMMER													
Energy Consumption Rate	kJ/min	120	109	122	122	121	92	121	116	112	115.01	9.76	8%
Time-Corr Specific Energy Consumption	kJ/liter	1,404	1,319	1,484	1,454	1,436	1,121	1,438	1,380	1,356	1376.87	108.78	8%
Specific Energy Consumption Rate	MJ/min/L	0.031	0.029	0.033	0.032	0.032	0.025	0.032	0.031	0.030	0.03	0.00	8%
Dry Fuel Consumed	g	326	297	332	331	328	252	327	314	304	312.40	25.88	8%
Total Energy Consumed	kJ	5,519	5,028	5,621	5,607	5,551	4,264	5,544	5,322	5,155	5290.05	438.30	8%
Energy Delivered to the Cooking Pot	MJ	2.011	2.268	2.412	2.069	1.963	2.207	2.208	2.142	2.289	2.17	0.14	7%
Average Cooking Power	kW	0.745	0.840	0.893	0.766	0.727	0.817	0.818	0.793	0.848	0.81	0.05	7%
Total Emissions													
COLD START		(cold start)	(cold start)	(cold start)	(cold start)	(cold start)	(cold start)	(cold start)	(cold start)	(cold start)			
CO	grams	19.67	20.50	27.18	16.35	16.29	16.46	23.89	20.13	17.91	19.82	3.72	19%

CO2	grams	390	454	540	497	494	476	505	521	429	478.47	47.08	10%
PM2.5	mg	1558	1423	1383	940	1093	926	1512	1086	1672	1288.17	280.26	22%
appx BC	mg	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!			
HOT START		(hot start)	(hot start)	(hot start)	(hot start)	(hot start)	(hot start)	(hot start)	(hot start)	(hot start)			
CO	grams	20.64	13.08	20.52	15.63	14.43	23.49	15.63	15.37	18.46	17.47	3.47	20%
CO2	grams	440	428	401	546	515	444	458	455	421	456.30	46.24	10%
PM2.5	mg	1140	1161	980	966	1156	1352	1063	1161	1116	1121.55	114.65	10%
appx BC	mg	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!			
SIMMER		(simmer)	(simmer)	(simmer)	(simmer)	(simmer)	(simmer)	(simmer)	(simmer)	(simmer)			
CO	grams	32.57	22.32	27.62	27.02	28.71	27.85	26.69	24.15	23.90	26.76	3.05	11%
CO2	grams	505	536	540	629	582	552	617	543	493	555.21	46.19	8%
PM2.5	mg	1353	673	1114	1086	951	908	1084	947	913	1003.35	187.03	19%

Appendix 2: Detailed performance results for used Ecoeye stove

Stove lab code		2019/B054			2019/B056			2019/B057					
Stove serial number		295181006151			295181001866			295181001226					
IWA Performance Metrics	**Units**	**Test 1**	**Test 2**	**Test 3**	**Test 1**	**Test 2**	**Test 3**	**Test 1**	**Test 2**	**Test 3**	**Average**	**STDeV**	**CoV**
High Power Thermal Efficiency	%	39.1%	43.6%	40.4%	37.5%	40.4%	39.7%	40.0%	39.4%	44.6%	40.5%	0.02	5%
Low Power Specific Consumption Rate	MJ/min/L	0.038	0.036	0.030	0.036	0.029	0.028	0.040	0.031	0.028	0.033	0.00	14%
High Power CO	g/MJd	8.38	7.99	10.87	9.47	9.43	8.57	8.91	12.52	8.43	9.40	1.45	15%
Low Power CO	g/min/L	0.20	0.14	0.15	0.21	0.13	0.15	0.17	0.11	0.12	0.15	0.03	22%
High Power PM	mg/MJd	505.3	522.1	527.9	490.5	635.2	469.5	676.3	521.4	476.2	536.05	71.61	13%
Low Power PM	mg/min/L	9.55	6.26	5.08	7.38	7.64	4.23	5.10	6.61	3.35	6.13	1.91	31%
Indoor Emissions CO	g/min	0.72	0.59	0.81	0.77	0.64	0.58	0.62	0.96	0.65	0.70	0.12	18%
Indoor Emissions PM	mg/min	34.6	38.5	39.3	35.6	42.9	31.8	42.1	37.8	37.1	37.75	3.52	9%
IWA Performance Tier		**Tier**	**Tier**	**Tier**	**Tier**	**Tier**	**Tier**	**Tier**	**Tier**	**Tier**	**Sub Tier**	**Tier**	
High Power Thermal Efficiency		3.4	3.8	3.5	3.2	3.5	3.4	3.5	3.4	3.9	3	2	
Low Power Specific Consumption Rate		2.0	2.3	2.8	2.2	2.8	3.0	1.9	2.7	2.9	2		
High Power CO		3.6	4.0	2.0	2.7	2.7	3.4	3.0	1.6	3.5	2	1	
Low Power CO		1.0	1.8	1.6	0.9	1.9	1.6	1.4	2.5	2.4	1		
High Power PM		1.7	1.7	1.7	1.8	1.5	1.8	1.5	1.7	1.8	1		
Low Power PM		0.8	1.4	1.7	1.1	1.0	1.9	1.7	1.3	2.3	1		
Indoor Emissions CO		1.7	2.2	1.4	1.5	1.9	2.2	1.9	1.0	1.9	1	1	
Indoor Emissions PM		1.2	1.0	1.0	1.1	0.9	1.3	0.9	1.0	1.1	1		
Standard Performance Measures													
Fuel to Cook 5L (850/1500)	g	847.0	779.7	732.9	820.8	731.3	720.1	874.2	737.2	661.8	**767.23**	68.52	9%
CO to Cook 5L (20)	g	63.1	50.1	58.3	67.7	50.9	52.6	57.1	51.7	43.8	55.04	7.28	13%
PM to Cook 5L (1500)	mg	3264.8	2591.2	2318.6	2711.8	3174.9	1995.1	2611.8	2583.5	1756.9	2556.50	490.44	19%
Energy to Cook 5L (15,000/25,000)	kJ	14,343	13,204	12,410	13,899	12,384	12,193	14,804	12,483	11,207	12991.83	1160.21	9%
Time to Boil	min	32.6	29.7	30.5	31.4	32.5	33.4	35.1	30.7	27.3	31.47	2.26	7%
CO2 to Cook 5L	g	1545.0	1397.7	1259.3	1401.3	1184.4	1107.4	1416.7	1050.5	970.0	1259.14	194.19	15%
Basic Operation													
COLD START													
Time to boil Pot # 1	min	39.30	35.90	36.18	39.02	32.92	37.70	38.75	37.52	32.25	36.61	2.57	7%
Burning rate	g/min	841%	878%	911%	860%	958%	874%	879%	857%	912%	8.86	0.36	4%
Thermal efficiency	--	0.37	0.41	0.40	0.36	0.40	0.38	0.35	0.38	0.41	**38.4%**	0.02	6%
Specific fuel consumption	g/liter	70.5	67.7	70.7	71.3	67.4	70.1	72.8	68.2	62.0	68.99	3.16	5%
Temp-corrected specific consumption	g/liter	72	67	72	72	69	71	78	71	63	70.55	3.99	6%
Firepower	watts	2374.7	2477.1	2569.9	2428.5	2702.5	2466.8	2480.5	2419.2	2574.3	2499.27	100.48	4%
Equivalent Dry Fuel Consumed	g	330.68	315.09	329.49	335.74	315.20	329.52	340.58	321.58	294.16	323.56	14.00	4%
HOT START													
Time to boil Pot # 1	min	24.50	23.82	23.72	23.47	30.60	28.20	26.98	21.28	21.68	24.92	3.08	12%
Burning rate	g/min	1216%	1105%	1216%	1295%	1011%	1121%	989%	1306%	1117%	11.53	1.14	10%
Thermal efficiency	--	0.41	0.46	0.41	0.39	0.41	0.41	0.45	0.41	0.48	42.7%	0.03	7%
Specific fuel consumption	g/liter	63.4	55.6	60.6	64.2	66.4	67.5	57.1	58.2	50.6	60.41	5.53	9%
Temp-corrected specific consumption	g/liter	65	55	62	64	68	69	61	61	51	61.76	5.63	9%
Firepower	watts	3432.4	3117.6	3431.7	3654.4	2853.0	3163.5	2790.1	3685.9	3151.9	3253.38	320.85	10%
Equivalent Dry Fuel Consumed	g	297.97	263.09	288.38	303.86	309.33	316.10	266.76	277.97	242.16	285.07	24.47	9%

SIMMER													
Burning rate	g/min	813%	750%	659%	781%	651%	629%	864%	687%	642%	7.19	0.85	12%
Thermal efficiency	--	0.4	0.5	0.5	0.4	0.4	0.4	0.4	0.4	0.4	43.1%	0.03	8%
Specific fuel consumption 45 min	g/liter	101	95	80	96	78	74	106	82	75	87.29	12.00	14%
Firepower	watts	2294.85	2115.77	1860.00	2203.96	1836.01	1775.67	2437.74	1937.95	1812.11	2030.45	240.10	12%
Turn down ratio	--	1.3	1.3	1.6	1.4	1.5	1.6	1.1	1.6	1.6	1.44	0.18	13%
Equivalent Dry Fuel Consumed	g	365.91	337.36	296.57	351.42	292.75	270.54	388.26	309.00	288.94	322.30	40.05	12%
Energy Consumption													
Net Calorific Value (dry)	kJ/kg	16933.5	16933.5	16933.5	16933.5	16933.5	16933.5	16933.5	16933.5	16933.5	16933.45	0.00	0%
Moisture Content	%	14%	14%	14%	14%	14%	14%	14%	14%	14%	14%	0.00	0%
COLD START													
Temp-Corrected Time to Boil	min	40	36	37	39	34	38	41	39	33	37.44	2.93	8%
Energy Consumption Rate	kJ/min	142	149	154	146	162	148	149	145	154	149.96	6.03	4%
Temp-Corr Specific Energy Consumption	kJ/liter	1,218	1,143	1,219	1,212	1,170	1,205	1,316	1,205	1,065	1194.69	67.61	6%
Specific Energy Consumption Rate	MJ/min/L	0	0	0	0	0	0	0	0	0	0.03	0.00	4%
Dry Fuel Consumed		346	328	342	347	328	342	353	336	306	336.44	14.06	4%
Total Energy Consumed	kJ	5,852.539	5,553.494	5,797.336	5,876.923	5,549.769	5,793.611	5,975.476	5,684.898	5,189.425	5697.05	238.11	4%
Energy Delivered to the Cooking Pot	MJ	2.087	2.201	2.217	2.040	2.117	2.129	2.011	2.051	2.039	2.10	0.07	3%
Average Cooking Power	kW	0.867278	1.026121	1.0034982	0.867898	1.046005	0.927202	0.8107816	0.873289	1.039711	0.94	0.09	10%
HOT START													
Temp-Corrected Time to Boil	min	25	24	24	24	31	29	29	22	22	25.49	3.30	13%
Energy Consumption Rate	kJ/min	206	187	206	219	171	190	167	221	189	195.20	19.25	10%
Temp-Corr Specific Energy Consumption	kJ/liter	1,097	938	1,044	1,091	1,152	1,161	1,032	1,028	869	1045.74	95.26	9%
Specific Energy Consumption Rate	MJ/min/L	0	0	0	0	0	0	0	0	0	0.04	0.00	9%
Dry Fuel Consumed		312	275	300	314	322	328	277	291	253	296.97	24.97	8%
Total Energy Consumed	kJ	5,284.591	4,650.603	5,083.760	5,323.538	5,447.830	5,560.606	4,693.952	4,927.634	4,286.534	5028.78	422.80	8%
Energy Delivered to the Cooking Pot	MJ	2.062	2.050	2.004	2.017	2.157	2.203	2.043	1.937	1.977	2.05	0.08	4%
Average Cooking Power	kW	1.372853	1.440101	1.3841692	1.426998	1.146821	1.282794	1.1825621	1.454287	1.499057	1.35	0.12	9%
SIMMER													
Energy Consumption Rate	kJ/min	138	127	112	132	110	107	146	116	109	121.83	14.41	12%
Time-Corr Specific Energy Consumption	kJ/liter	1,711.156	1,600.614	1,350.362	1,628.094	1,315.615	1,255.711	1,787.099	1,380.235	1,274.470	1478.15	203.26	14%
Specific Energy Consumption Rate	MJ/min/L	0	0	0	0	0	0	0	0	0	0.03	0.00	14%
Dry Fuel Consumed	g	374	345	302	361	300	275	399	315	295	329.56	41.77	13%
Total Energy Consumed	kJ	6,338.190	5,843.056	5,114.579	6,105.525	5,082.406	4,663.133	6,750.012	5,340.471	4,987.240	5580.51	707.35	13%
Energy Delivered to the Cooking Pot	MJ	2.554	2.724	2.384	2.559	2.108	1.960	2.372	2.259	2.144	2.34	0.25	11%
Average Cooking Power	kW	0.95	1.01	0.88	0.95	0.78	0.76	0.88	0.84	0.79	0.87	0.09	10%
Total Emissions													
COLD START		(cold start)	(cold start)	(cold start)	(cold start)	(cold start)	(cold start)	(cold start)	(cold start)	(cold start)			
CO	grams	16	17	21	21	18	20	21	20	18	19.18	1.95	10%
CO2	grams	545	509	473	515	483	496	528	431	397	486.24	47.38	10%
PM2.5	mg	1064	1148	1022	795	1262	957	1532	1087	926	1087.92	213.72	20%
appx BC	mg	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!			
HOT START		(hot start)	(hot start)	(hot start)	(hot start)	(hot start)	(hot start)	(hot start)	(hot start)	(hot start)			
CO	grams	19	17	24	17	23	17	15	30	16	19.67	4.85	25%
CO2	grams	460	415	380	443	454	455	476	380	341	422.73	45.96	11%

PM2.5	mg	1033	1071	1193	1193	1454	1078	1207	994	985	1134.25	147.47	13%
appx BC	mg	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!			
SIMMER		(simmer)	(simmer)	(simmer)	(simmer)	(simmer)	(simmer)	(simmer)	(simmer)	(simmer)			
CO	grams	32	23	25	35	22	25	28	19	20	25.51	5.25	21%
CO2	grams	731	646	599	654	514	459	648	472	447	574.49	103.42	18%
PM2.5	mg	1556	1005	851	1213	1296	695	845	1128	579	1018.53	310.70	31%

Appendix 3: Analysis of test results

The measured data was checked, verified and the Coefficient of Variation (CoV) done across the three tests for each stove to make sure the results were consistent and were true results obtained from the stove performance tests. The recommended limit for CoV on Fuel use/Efficiency and bench mark values is 25%. The test results were summarized using the tiers of performance. The tiers of performance were developed by the International Standards Organization (ISO)/International Workshop Agreement (IWA) (*IWA 11:2012*)[1]

Table 4. Performance indicators and respective metrics

Performance indicator	Metrics	Units
Efficiency/Fuel Use	High power Thermal Efficiency	%
	Low power Specific Consumption	MJ/min/L
Emissions	High power CO	g/MJ_d
	Low power CO	g/min/L
	High power PM	mg/MJ_d
	Low power PM	mg/min/L
Indoor emissions	Indoor emissions CO	g/min
	Indoor emissions PM	mg/min
Safety	Points from 10 weighted safety parameters	Points

Basing on the results, the stoves were categorised under different tiers of performance according to ISO/IWA guidelines, as follows:

Table 5. Tier levels and their explanations

Tier	Explanation
Tier 0	No improvement over open fire / baseline
Tier 1	Measurable improvement over baseline
Tier 2	Substantial improvement over baseline
Tier 3	Currently achievable technology for biomass stoves
Tier 4	Stretch goals for targeting ambitious health and environmental outcomes

(Source: PCIA/GACC, 2012)

Table 6. Tier levels Values of IWA performance metrics used to categorize stoves

Performance indicator	IWA VITA WBT Tiers	Units	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4
Efficiency/Fuel Use	High Power Thermal Efficiency	%	<0.15	≥0.15	≥0.25	≥0.35	≥0.45
	Low Power Specific Consumption	MJ/min/L	>0.05	≤0.05	≤0.039	≤0.028	≤0.017
Emissions	High Power CO	g/MJd	>16	≤16	≤11	≤9	≤8
	Low Power CO	g/min/L	>0.2	≤0.2	≤0.13	≤0.1	≤0.09
	High Power PM	mg/MJd	>979	≤979	≤386	≤168	≤41
	Low Power PM	mg/min/L	>8	≤8	≤4	≤2	≤1
Indoor emissions	Indoor Emissions CO	g/min	>0.97	≤0.97	≤0.62	≤0.49	≤0.42
	Indoor Emissions P	mg/min	>40	≤40	≤17	≤8	≤2

[1] Guidelines for Evaluating Cookstove Performance available at http://www.iso.org/iso/catalogue_detail?csnumber=61975